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RECOMMENDATIONS FOR METEOROLOGICAL DATA COLLECTION DURING PHYSIOLOGICAL FIELD STUDIES

U S ARMY RESEARCH INSTITUTE OF ENVIRONMENTAL MEDICINE

Natick, Massachusetts

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by

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February, 1994

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EXECUTIVE SUMMARY

Adequate meteorological data are primary environmental requirements that should be collected during physiological field studies. This report describes the minimum and recommended levels of meteorological data collection during winter field studies. Cold weather models and indices are briefly discussed. Meteorological data collected by an automated weather station during a January, 1988 field study at the Marine Corps Mountain Warfare Training Center, Bridgeport, CA are presented.

I. INTRODUCTION

A. Military relevance of cold weather problems

The most direct way to summarize the military importance of cold weather is to state that the battlefield situation is confounded by cold weather. The tactical requirements remain constant, but almost every supporting element is altered or impacted by the cold. Battlefield problems include losses due to cold injury, reduced efficiency in heavy, bulky winter clothing, weapon malfunctions, material failures, more frequent troop rotations and time spent in rewarming shelters. Logistically, additional clothing and food are required and additional difficulties are experienced in the following areas: delivery of water; delivery and handling of Petroleum, Oil and Lubricants (POL) supplies (including additional fuel needed for warming); repairs are more difficult; transport problems appear, and everyone needs better shelter (Maginnis, 1991).

In terms of medical concerns, drugs and blood must be protected from the cold, and casualties may suffer from exposure and frostbite as well as their wounds (Alexander, 1986; Cowdrey, 1987; Hamlet, 1988; Trotter, 1991; Young et al., 1992; Burr, 1993). Although cold injuries and hypothermia are usually associated with cold exposure, overheating and dehydration may also occur. In addition, patients must be sheltered and kept warm and their evacuation by helicopter or ground may be slowed by adverse weather. A final medical and tactical concern is that many cold injuries are permanently debilitating; even relatively minor cold injuries can severely impact troop strength.

The nature of the impact of cold and its severity varies with the weather. The US Army recognizes two categories of cold weather: wet-cold and dry-cold. The differences between the two categories are determined by temperature range, ground

moisture and precipitation. Wet-cold is associated with higher temperatures (0°C [32°F] to approximately 16°C [60°F]), liquid precipitation (Burr, 1993) and non-freezing cold injuries, especially immersion foot, and wet clothing due to external moisture. Dry-cold is associated with temperatures below 0°C (32°F) and precipitation as snow (Burr, 1993). In dry-cold, frostbite is the more common form of cold injury and sweat is the primary cause of wet clothing insulation. Whayne and DeBakey (1958) noted that a transition in cold injuries from immersion foot to frostbite could be clearly related to a change in air temperature. As temperatures increased, thawing occurred, and the incidence of trenchfoot/immersion foot increased. Conversely, the incidence of frostbite increased in relation to the occurrence and duration of temperatures below freezing because frostbite can only occur if tissue temperatures fall below the freezing point of tissue.

Because the presence of liquid water is a more important criterion than the freezing temperatures for the purposes of clothing issue, the weather is usually categorized as wet-cold when field conditions encompass the freeze-thaw transition. The increased resistance to external water of the Extreme Cold Weather Clothing System (ECWCS) and intermediate cold-weather boot have simplified the problem of clothing issue during freeze-thaw periods. The distinction between wet-cold and dry-cold still has some utility because the ECWCS parka shell may not be suited for extreme cold (Maginnis, 1991).

B. Meteorology for military research

1. Thermal models

A model is a representation of the function of a system. Models may be descriptive, empirical, mathematical, or physical. The research effort to develop mathematical models which predict when environmental conditions present a potential for cold injury is important. By providing quantitative predictions of the risks of cold injuries, these models may contribute to effective mission planning. An awareness of potential manpower losses due to the cold may lead to the reconsideration of mission strategies, but are more likely to afford an opportunity to adjust clothing and supply requirements and to plan for casualty evacuation and treatment of cold injuries.

Indices, such as the Wind-chill index (Siple and Passel, 1945) are essentially empirical models that relate values along a scale to specific conditions or responses. The database for development and evaluation of thermal models requires adequate meteorological data (Santee et al., 1994).

2. Priority for meteorological data

Models are particularly valuable because they can be used to provide "expert" guidance to the commander. Although indices and models are clearly valuable, the collection of the basic meteorological data is the most important factor. In the absence of models, meteorological data allow commanders and their staff to use experience and common sense to plan for the impact of weather on operations. Common sense works better when soldiers have measured values, and know, for example, that "cold" means 0°C rather than 5°C. Both conditions are cold, but below 0°C frostbite can occur, whereas above that limit non-freezing cold injuries and hypothermia can occur. Even if models or indices are used. meteorological data are needed as inputs. The most critical element in predicting the impact of environmental conditions on military operations is not a specific model or index, but meteorological data.

C. Meteorology for physiological studies

1. Basic requirements

Because meteorology has a significant impact on military operations, the collection of meteorological data should be incorporated into the design of field studies. What constitutes an adequate meteorological database? At the very least, the study database should record the weather information that would be available to a commander at the time of the field operation. The data should be in sufficient detail to recreate the commander's perception of the prevailing weather. At the company level, there is little data available except simple air temperature readings and rough estimates of wind speed, whereas at higher command levels there is access to the Integrated Meteorological System (IMETS) and other relatively sophisticated meteorological data.

Ideally, meteorological data collected should exceed the minimum company level standards (e.g., air temperature and estimated wind speed) and should be adequate to support physiologically-based weather models such as effective temperatures (ET^*), operative temperature, etc. (Gonzalez, et al., 1974) and new model development. A sound meteorological database would consist of continuous data on the four basic meteorological parameters: temperature, wind speed, humidity and solar/thermal radiation. The data should be collected with standard meteorological instruments and methods in the soldier's immediate spatial environment.

2. Human-scaled meteorology

The value of currently available meteorological data is constrained because the data are not scaled spatially to soldiers in field environments. It is "intuitively obvious" that meteorological data should be collected on a scale relevant to the environment of the individual soldier (human scaled). However, weather data are often orientated towards the operation of equipment, such as armored vehicles, helicopters or other aircraft that deliver the heaviest firepower. Information, whether in science or the tactical battlefield, has a cost. Human-scaled weather is often not critical as long as the soldier's mechanical support functions. Machines may malfunction and deteriorate in the cold, but people suffer from the cold. To develop tools that reduce the risk of cold injuries and may enhance individual soldier performance, the meteorological data normally provided by weather support units needs to be supplemented by focused, on-site data collection.

The soldiers' environment is often defined spatially by their tasking and capabilities and by time. In a 24 h period, a foot soldier in a defensive position may occupy a relatively limited spatial environment of a few square feet, with a vertical dimension ranging from the ground to head height. The thermal environment, i.e., the source of environmental stress during that period, is defined by air temperature, humidity, air movement and radiation within that spatial environment. Those four parameters are partially independent and vary temporally. If the soldier moves, his spatial environment increases. The spatial bounds of a mechanized or airmobile soldier are much greater, but only a subset of all possible combinations are encountered because a soldier moving through an environment is essentially collecting a time-space defined subset of the total possible environments. A larger unit samples a larger space.

D. Minimal instrumentation set

Researchers, working with small ground units that have minimal mechanized equipment, need simple, lightweight field weather instruments. In the cold, battery-powered devices must either be kept warm or frequently recharged, so ideally a basic instrument set should not be dependent on battery power. An example of a simple weather kit for temperatures down to freezing is the Weather Observation Kit (FSN# 6660-01-2638). The kit was originally designed for forest fire fighting operations. It contains a simple tube anemometer which operates on the Bernoulli principle, and a sling psychrometer with both wet- and dry-bulb thermometers. A compass is also included to provide a reference for wind direction. Although some values may be derived from wet-bulb thermometers below 0°C, the freezing point of water is for most purposes the lower limit for sling psychrometers. The Weather Observation Kit provides some information for supporting air operations, but does not provide any data regarding solar radiation. A Wet Bulb Globe Temperature (WBGT) kit does provide some limited information about solar load. However, the standard black globe thermometer is bulky, and it is not possible to calculate mean radiant temperature (T_{mrt}) from only air, black globe, and natural wet-bulb temperatures. In addition, the naturally aspirated wet-bulb thermometer has the same temperature limitation as the sling psychrometer. WBGT instrument kits are not suitable for cold weather use because the WBGT index (Yaglou and Minard, 1957) is meaningless as a predictor of possible cold injury and, due to the absence of a wind speed value, even the wind-chill index can only be an estimate.

1. Individual parameters

a. Temperatures

Descriptive meteorology should be comprehensive. It should consist of more than average temperature, which can be particularly misleading if temperatures cross the freeze-thaw threshold, or if only minimum temperatures are presented because of a very human tendency to use extremes to define conditions. If someone indicates they

bivouacked at -40°C, they usually mean that the temperature dropped to a minimum of -40°C, whereas the average overnight temperature may have been -32°C and the daily average -28°C, with a maximum temperature of -18°C. If an AC power supply or battery-powered datalogger can be supported, a continuously recording datalogger will provide minimum-maximum (min-max) and average values. Otherwise, both a shaded dry-bulb thermometer and a min-max recording thermometer should be part of the cold-weather kit. An alcohol pocket thermometer may be equipped with a pre-measured string so that it will hang at a preselected height. The thermometer may also be fitted with a simple cup or disc to shade it from direct sunlight. The min-max thermometer should also be placed out of direct sunlight.

Another meteorological parameter important in the cold is the temperature threshold for water to ice phase changes. Overnight minimum temperatures are of particular interest if the study includes outdoor bivouacs. A continuously recording data logger will provide the min-max temperature range and the freeze-thaw transition point simply as by-products available either by inspection or as a specific output of the data acquisition system. Simpler min-max recording thermometers are readily available. The primary concern with the use of a min-max thermometer is selecting the recording time(s). For a short study of less than twenty-four hours, the obvious interval is the duration of the study period. With a continuous recording datalogger, the interval can be the actual 24-hour period for each day. For recording min-max temperatures over a twenty-four hour interval with hand-held instruments, it is often wiser for management to set the recording and reset time at a more reasonable time than midnight.

Ground or surface temperature is often a neglected measurement even though it should be clear that a standing soldier's feet, and any individual sitting, lying or sleeping on the ground, including casualties, will be impacted by cold ground temperatures. In addition, to an individual occupying a foxhole or other temporary field fortification, ground temperature may be as important as air temperature. Surface snow melt is also a factor of concern, and ground or surface temperature may indicate when there is sufficient radiation to reach the critical transition phase.

b. Radiation

Incoming natural radiation in the ultraviolet (UV), visible (solar) and infrared (thermal) spectra is an important physiological parameter. In this paper the term radiation will refer specifically to incoming UV, solar, and IR radiation, but not to the ionizing radiation which would be a factor on the nuclear battlefield. It is important to understand that some radiation instruments have very specific spectral ranges. Most instruments do not measure short-wave UV radiation even though it can have significant effects, including sunburn and snow blindness. Incoming solar radiation may also contribute to snow melt, which will affect both clothing insulation and transport.

In terms of basic instrumentation, radiation data are very desirable. The simplest instrument is the Vernon or black globe thermometer (Vernon, 1932; Wenzel and Forsthoff, 1989). In its original form the black globe thermometer consists of a thermometer inserted into the center of a hollow 15 cm (6 in) diameter copper sphere painted matte black. The black globe is part of the basic Wet-Bulb Globe Temperature (WBGT) monitoring set described in FM 21-10 (1988) and TB MED 507 (1980). One objection to the Vernon globe is its bulk; several miniaturized black globe thermometers exist which may offset this problem. Another objection to the black globe thermometer is that the measured temperature (T_{bg}) is really a composite of the interaction of air temperature, wind speed and both thermal and solar radiation. To utilize T_{bg} in physiological studies, air temperature, T_{bg} and wind speed are all used to calculate a mean radiant temperature (T_{mrt}). It is important to emphasize that a WBGT instrument set does not collect an independent value for wind speed, and consequently, T_{mrt} cannot be calculated from only a WBGT data set.

The globe or spherical shape of the Vernon thermometer may be a problem depending on how radiation is perceived by the investigator. Incoming solar radiation impacts the body in three ways. Direct solar radiation is "line-of-sight" rays of solar energy that impact the body at varying angles depending on body posture, latitude, time of day and time of year. Diffuse solar radiation is deflected by the atmosphere and is received with approximately the same intensity over all parts of the body that are exposed to the sky. Reflected solar radiation consists of all the solar energy that strikes the ground and is reflected back onto the body. Reflected solar energy

depends on the intensity of the incoming radiation and the reflectivity or albedo of the ground surface. The "collection area" for reflected radiation is analogous to that for diffuse radiation; i.e., essentially all body surfaces exposed to the ground receive the equivalent amounts of reflected radiation. Snow, ice and rock surfaces have a high albedo and the intensity of solar radiation may be much greater than initially anticipated. Surface albedo is often a factor in both sunburn and snow blindness.

By using a sphere as the sampling surface, a Vernon thermometer is not affected by solar angle, i.e., the direction of the incoming direct solar radiation. A sphere always presents the same surface area normal to the solar rays regardless of the angle of the rays. In many physiological studies, assumptions are commonly made regarding surface areas and T_{mrt}, and the net result is a relatively uniform treatment of radiation made without regard to time of day. Most studies assume a "standing man." More realistically, both the posture of the individual and the solar angle should be considered. In the simplest data collection situation, with a basic Vernon or black globe thermometer (assuming air temperature and wind speed are also measured), there is insufficient data to consider any radiation component except T_{mrt}. There are no data regarding direct versus diffuse solar radiation. As a consequence, when a globe thermometer is used to measure radiation, there can be no adjustments for the interaction of solar angle and posture.

Finally, incoming "sky" and "ground" thermal radiation are analogous to diffuse and reflected solar radiation in terms of the collection areas. There is no thermal radiation analogue to direct solar radiation. Thermal radiation may be measured with net radiometers that measure both solar and thermal radiation, and then the solar component, measured with a pyranometer, is subtracted from the net sum of solar and thermal radiation. Estimates of thermal radiation may also be calculated from ground and air temperatures (Santee and Gonzalez, 1988).

c. Humidity:

Humidity is a general term that refers to the moisture content of the air. There is some confusion regarding humidity because it can be expressed in a variety of ways, including relative humidity, absolute humidity, dew point temperature and water vapor

pressure (Santee and Gonzalez, 1988). Meteorological instruments normally measure either relative humidity or dew point temperature. When relative humidity or dew point values are collected in conjunction with other environmental parameters, especially dry-bulb temperature, it is possible to convert those values to other units.

The impact of humidity in cold weather is not readily understood. Intuitively, we "feel" the impact of damp cold, but when even saturated cold air is warmed, it becomes "dry" in terms of its capacity to absorb additional water. In this particular situation, the concept of dew point is particularly useful because it very clearly indicates the relationship between water vapor saturation and temperature. The physiological importance of humidity is that it determines the rate of water vapor transfer between skin and respiratory surfaces and the external environment. Hence, humidity determines evaporative cooling potential and to a lesser degree, impacts hydration status. Low humidity significantly increases respiratory water loss.

Humidity is often difficult to measure below 0°C. In extreme cold, humidity may not be a critical variable for human physiology because paradoxically even saturated air is dry when warmed to physiological active temperatures. Respiratory water loss may be increased in cold weather. Inhaled air is warmed to body temperature as it enters the lungs, with a subsequent increase in water vapor carrying capacity. Water from respiratory surfaces saturates the dry air and is lost to the environment upon exhalation. Water vapor losses often condense in cold air or against a cold barrier leading to visible breath, fogged windows and steaming from warm, damp surfaces.

In cold weather clothing is obviously important. It is therefore useful to consider the interaction of evaporative water loss from the skin and clothing. The following summary is derived from Gonzalez's (1987) overview of the problems of clothing. When water vapor recondenses within the clothing layer, several things may happen. First, if the soldier is overheating, recondensed sweat does not provide any evaporative cooling. Second, when there is a phase transition from vapor to liquid, heat is released. Third, the moisture in the clothing may reduce the effective insulation of the clothing. Finally, if there is liquid on the skin surface, the soldier is more likely to feel uncomfortable (Gagge et al., 1969).

d. Wind speed:

Wind speed is difficult to measure because it is often dynamic, with constant fluctuations in velocity and direction. The siting of the wind-speed monitor is important. Wind speed varies with height above ground, nature of vegetation on the ground and obstacles to wind flow on the ground. Very close to the ground wind speed is lower and more turbulent, due to drag or friction as air passes over ground. There is a standard method for estimating wind speed at different heights if wind speed is measured at two heights (Platt and Griffiths, 1966; Campbell, 1977). However, for studies of standing human, a direct measurement at measure at 1.5 to 2 m height is usually sufficient.

Wind speed data recorded by hand once every hour are often misleading because of almost constant wind fluctuations. With hand-held instruments, it is simply not practical to continuously record wind speeds. Even with an individual assigned solely to collecting meteorological data it will, in fact, be difficult to record a wind speed every 15 minutes. In addition, a hand-held anemometer may be influenced by the presence of the individual holding the device. When possible, the instrument should be mounted in a well-exposed position (taped to the top of a stick, etc) and the reader, standing away from the instrument, should be carefully positioned to avoid wind blockage. However, most compact hand-held anemometers are not amenable to "stand-off" use.

When meteorological data are collected by an individual with hand-held instruments, there a practical limit to the intensity of that data collection effort. A constant recording anemometer that can be used to generate mean data for a selected time interval is more desirable than a simple hand-held instrument. The time interval for sampling and averaging wind speeds is a matter of debate, with suggestions ranging from every second to twenty-four hours. From a practical perspective, the sampling intervals may be 5 to 60 seconds and the averaging period may range from 1 to 15 minutes if a recording anemometer is used.

2. Basic data requirements and collection site

Physiological studies have differing objectives. The authors' inherent bias is towards relatively short-term (2-24 h) studies of active soldiers. However, nutritional studies may often need to monitor soldiers for a prolonged period of 30 days or longer. It is simply not practical to collect hourly data of all parameters with hand-held instruments for a month. The absolute minimum data requirements for short-term winter studies (<24 h) of active soldiers are hourly measurements of air temperature. During more prolonged studies, in addition to daily mean temperature, values for minimum and maximum temperature are very desirable. If activity is very site specific, then measure at that site. If the study is conducted in an area with a generally uniform environment, select a representative site, with special attention to siting of wind speed measurements. The presence of vegetation, vehicles and observers may unnecessarily bias wind speed measurements and an investigator must use good judgement in selecting a monitoring site.

The individual assigned to weather monitoring should also keep a weather log. Although the emphasis of this paper is the systematic collection of quantitative meteorological data, a written log or diary of weather events and observation is also valuable. In particular, records of cloud type, estimates of percent cloud coverage, precipitation events, and other short term weather phenomena are quite useful. On more than one occasion the authors have attempted to reconstruct weather events from individual instrument records when a simple log entry, such as "...at 12:33 it clouded up and a light drizzle fell for approx. 15 min" would have been of considerable assistance. A book illustrating cloud type and formations is also a useful aid in describing visual weather events. It is generally useful to make general weather observation in the log after each data collection and to supplement those systematic observations with additional observations as they occur. A standard time for recording and resetting min-max thermometers and precipitation gauges (or estimates if there are no gauges) is also recommended.

Table 1. Recommended contents of a cold weather kit for small units

1. alcohol thermometer
2. min-max recording thermometer
3. anemometer
4. black globe thermometer
5. ground temperature probe
6. dew point or humidity sensor
   a) above freezing:
      sling psychrometer w/supplies
   b) below freezing:
      hair hygrometer or electronic sensor
7. 6" ruler
8. compass
9. waterproof notebook and pencil

E. Automated weather data collection station

For a scientific physiological study with adequate resources, continuous meteorological monitoring by an automated weather station is strongly recommended. With an automated system, data are monitored and continuously averaged over selected intervals and recorded in both printed and taped format and observer does not have to be present to collect data. Several commercially packaged weather stations are available, but the authors have assembled their automated weather stations by selecting a datalogger and individual weather instruments rather than purchasing a complete station package. It requires extra effort and knowledge to assemble a custom station, but some commercial station packages do not collect an adequate physiological database. In particular, most commercial stations collect minimal radiation data. Commercial weather stations designed for scientific or industrial use often incorporate professional weather instruments. The individual instruments may be listed individually in the same catalogue and their basic station packages may be customized with additional instruments. Simpler "home" stations are often designed for an AC power supply and may not be designed for extreme cold. Catalogue information is often not very specific regarding low temperature operations of humidity sensors or battery-power supply problems at extreme temperatures. It is also useful to have some capability to expand the number of sensors for both redundancy of critical sensors and additional inputs, such as low-level and ground temperatures.

1. Recommended measurements

The basic requirements remain the same: temperature, wind speed, solar/thermal radiation and humidity. With an automated station, there is an expanded capability to record more values and to utilize more sophisticated instrumentation. Table 2 contains an expanded list of recommended meteorological measurements to support physiological studies. To the basic single air temperature at a height of 2 meters can be added measurements at 0.5, 1.0, and 1.5 m plus ground temperature (5 cm below surface). A cup anemometer should be substituted for the hand-held anemometer. A black globe thermometer may be retained, but more sophisticated monitoring of solar radiation is desirable. We recommend two pyranometers, one placed in the open to monitor global radiation, and one shaded by a shadowband to record diffuse solar radiation. An electronic capacitance humidity sensor may be substituted for the sling psychrometers and hair hygrometer. Manufacturers' specifications claim these sensors operate at -40°C. Santee and Gonzalez (1988) present a more detailed discussion of instrumentation for physiological studies. Simple rain and snow gauges should also be included whenever possible and their reading systematically recorded in a weather log.

Table 2. Recommended data set for a data acquisition/recording system

1. shaded air temperature
    a) primary air temperature at head height (2 m)
    b) supplemental values at 0.5, 1.0 m, 1.5 m (torso)
2. ground temperature
    primary sensor 5 cm below surface
3. wind speed
4. solar/thermal radiation
5. humidity
6. climatic data
    a) 24-h mean, daily minimum and maximum temperatures
    b) precipitation-events record
    c) amount of precipitation
    d) freeze-thaw observations
    e) frontal activity
    f) cloud type and coverage

2. Instrument calibration and setup

Standards for calibration are generally stated for each type of instrument by the manufacturer. Each type of instrument requires pre-deployment checks against a calibrated instrument or test environment. During these checks, each instrument is setup, hard wired and programmed into the datalogger and run. The trial runs may be conducted in a controlled environment or outdoors depending on the type of instrument and the parameter being measured. Multiple instruments may be run simultaneously to verify calibration. A logbook is maintained with each datalogger to record calibration checks, hard wiring, individual instrument calculation constants, programming, output units, and a record of input/output channels. Changes made during file setup should also be carefully recorded.

3. Instrumentation costs

Sophisticated weather monitoring has several costs, including the direct costs of a datalogger ($2-3K), humidity sensor ($1K), pyranometers ($0.4 to 1.5K each) and shadowband ($1.5K). The second cost is set-up. Most of the instruments can be mounted on simple platforms or a mast, but the shadowband requires careful set-up and adjustment (Appendix A). The third cost is for a power supply. Most field datalogger can use battery or AC current power supplies. If the study area is in close proximity to an AC source and power can be supplied safely, then a major problem is resolved. The alternatives are generator power and battery power. Generators require monitoring, fueling and possibly maintenance and generate noise. Batteries are cleaner and quieter than generators, but cold reduces their effectiveness. Batteries can be replaced or measures may be taken to maintain battery life. To maintain battery life, the datalogger can be placed in an insulated container, such as a beverage cooler, with a heat source such as containers of heated sand, salt or even a hot water bottle. The heat source should be replaced periodically depending on the rate of heat loss.

II. DEMONSTRATION METHODS

A. Introduction

This section contains the description and instructions for the operation of an automated weather station, including the data collection program written for the Campbell 21X datalogger (Campbell Scientific, Logan, UT). The weather station collected barometric pressure, air and ground temperatures, black globe temperature, wind speed, global solar radiation and diffuse solar radiation. The original program included a humidity sensor, but the available instrument was not satisfactory in terms of both calibration and excess power requirements. Therefore, the humidity sensor was eliminated from the program. Santee, et al., 1992 presented the instrumentation and data collected during a physiological study in a hot-dry climate (Fort Bliss, TX).

The weather station was located in open alpine meadows at the U.S. Marine Corps Mountain Warfare Training Center, Bridgeport, CA, at 2,200 and 2,550 m elevation. Exact conditions and facilities could not be determined without actual inspection, so instructions were written for the operator. The instructions were thorough and contained some very pragmatic information concerning the setup and operation of a portable winter weather station. To retain that information, <u>the instructions are presented below as they were given to the station operator</u>. The programming instructions for the datalogger and a program listing have been placed in Appendix A.

B. Operating instructions

1. General

The following equipment is designed to provide automatic data collection of meteorological data for physiological studies of human performance at the Marine Corps Winter Warfare Training Center, JAN 88. The data collected will be air temperature (T_a) at 0.5, 1.0, 1.5 and 2.0 m, ground temperature (T_g) at 5 cm below the surface, black-bulb temperature (T_{bg}) at 1.3 m, wind speed (v) at 2 m, pressure (P) at 1 m, global (I_g) and diffuse (I_d) solar radiation. We do not have a reliable field humidity sensor for temperatures below 0°C. A field weather belt kit containing a sling

psychrometer with wet and dry bulb temperatures and a simple wind gauge will be provided to allow additional on-site .ield measurements.

2. Site

Exact conditions and facilities cannot be determined without actual inspection. Ideally a good data collection site would be a level open area with no obstructions located within distance equal to 10X their height from the wind gauge. In the absence of an "ideal" site, a representative site in proximity to the work/living site with representative exposure, especially in the prevailing wind direction(s). Wind flows may be up and down slope or channeled by local topography. No shadows should fall on the radiation instruments (black globe thermometer or pyranometers).

3. Setup

Three instrument bases must be set up. The two rectangular stands for the pyranometers should be leveled. The stand with the shadowband should be oriented so the curve of the band opens to true north. The instructions included for the shadowband setup are correct, but somewhat unclear at points. The following is a brief synopsis for setting up the shadowband:

a) Orientate the base N-S with the band at the south end and the pyranometer platform on the north end.

b) Assemble the shadowband components as per the picture in the diagram

c) Set the latitude adjustment scale on the side at the site latitude (use the appropriate topographic map to find latitude)

d) Set the sliding declination scale (supports band, has wing nuts) at 0°.

e) Use the sliding base scale to line up the center of the sensor platform (N-S) through the small holes in the end of the band.

f) Place the pyranometer (sensor) on the semi-circular platform

g) Use the same sighting holes to line up the dome of the sensor by sliding the base of the sensor platform up and down (use Allen wrench)

h) Use set screws in base of pyranometer to level the sensor, then use additional screws to attach sensor to base. Check the pyranometer serial number so that the correct program multiplier is used to calculate the radiation.

i) Set the sliding declination scale. During the winter in the northern hemisphere all declination values are negative. The approximate declination can be determined from the 1979 Ephemeris page enclosed. The value should be in the low twenties or upper teens.

j) Check the shadow cast if possible under bright sunlight throughout the day and make minor adjustments to the declination and N-S orientation.

The second pyranometer (global) should be set up on a level base without any significant shading or reflecting surfaces within 2 m. Follow step 8 to properly level the instrument and record the serial number in your notebook.

The mast for the wind gauge ideally should be rigid but the improvised base provided will not prevent some flexing. The base should be weighted and the mast guyed if possible. Consideration might be given to freezing the base in place by placing it on a packed snow base (or bare ground), weighting or burying it with sandbags, rocks or snow, then pouring water over the base. Before freezing the base in place however, give thought as to how it will be recovered without damaging the base. The thermocouple thermometers should be placed at 0.5, 1.0, 1.5 and 2.0 m. They can be suspended from either the wind mast or the pyranometer base. The radiation shield reflectors should be used at 1.0, 1.5 and 2.0 m. If the 0.5 m thermocouple is placed under a pyranometer base, it should be shaded enough. The black globe thermometer should be suspended at 1.3 m (4 ft) far enough out that it will not swing against the base. The barometer can also be mounted on a pyranometer stand. I suggest a height of 1 m, but that is not critical. The small opening next to the connector should be oriented downward.

Cables to the instruments should be anchored with some slack to allow for wind or accidental pulls. The cables should be run through the side ports and wired into the data logger prior to attaching the cables to the instruments. The battery should not

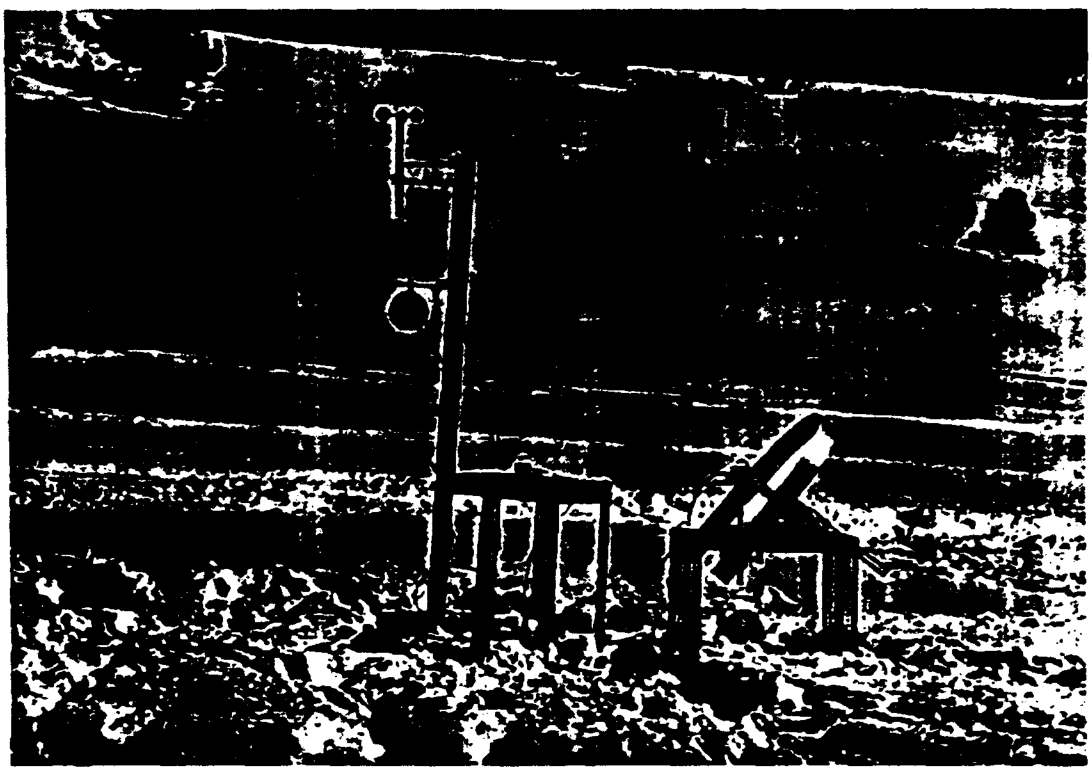
run down below 10 V (They must be replaced before they run down to 9.6 V). The printer has similar limits and should be recharged whenever possible with the AC adapter. The temperature limit for the printer is -15°C. Batteries may run down quickly in the cold. If a suitable warmed mass (bags or cans of salt or sand, hot water bottle, etc.) is placed inside the cooler with the logger and printer, problems with cold weather operations should be minimized. Care should be taken to avoid overheating (60°C for the logger). Turn off the recorder when the study is completed to avoid excess battery discharge.

III. DEMONSTRATION RESULTS

A. Introduction

This section presents the meteorological data collected 20-28 January 1988 at the Marine Corps Mountain Warfare Training Center, Bridgeport, CA during a USARIEM field study (Hoyt, et al., 1991). Figure 1 shows the weather station in operation. There was snow cover throughout the study. Site elevations ranged from 2,200 to 2,550 m. Day 1 of the study corresponds to 21 January 1988. On 25 January 1988 an interruption in the data set indicates when the weather station was moved from a site at an elevation of 2,550 m to 2,210 m. The shadowband was incorrectly setup and no useable diffuse radiation values were obtained.

Figure 1. The weather station in operation at Pickel Meadows, January 1988.



B. Meteorological data from 1988 field study

Table 3 presents the air and ground temperatures measured at the USMC Mountain Warfare Training Center at Bridgeport, California (Pickel Meadows). Data include 24 h mean values and the minimum-maximum extreme range. Figure 2 presents the air temperatures measured at 2 m for 21 to 27 January 1988, plus an indication of the 24 h mean temperature for each day. Figure 3 indicates the influence of solar radiation by plotting both air and black globe temperature against time for 21-27 January 1988. Figure 4 shows the global radiation values for the same six days and helps demonstrates the problem with black globe. January 26th was a day of relatively low solar radiation, as reflected by both the decreased black globe and global radiation values (mean global value 255 $W \cdot m^{-2}$, maximum value 473 $W \cdot m^{-2}$). The black globe values for 27 January appear to indicate the same situation, but the global radiation values, which are not influenced by wind speed (Figure 5) suggest that the depression of black globe on 27 January does not reflect the incoming radiation on that day (Mean 289 $W \cdot m^{-2}$, maximum 704 $W \cdot m^{-2}$). Figure 6 illustrates the classical pattern of wind-speed distribution (23 January), with the calmest periods near sunrise and sunset. When compared to the complete six-day distribution of wind speeds (Figure 5), the hazard of assuming a classical distribution of wind speeds is quite apparent.

Table 3. Air and ground temperatures 21-27 January 1988

Date	21 JAN	22 JAN	23 JAN	24 JAN	26 JAN	27 JAN
T_{grd}*	-6.9	-9.1	-7.2	-8.0	-3.8	1.3
T_a**	-6.7	-4.3	-1.1	-2.9	-1.2	2.9
maximum***	-1.5	6.4	8.1	8.4	6.5	10.2
minimum	-14.9	-12.8	-9.1	-10.4	-8.5	-3.5

*24 h. mean ground temperature **24 h. mean air temperature at 2 m *** maximum air temperature (T_a) at 2 m

Figure 2 Six-day air temperatures at 2 m plus 24-h means

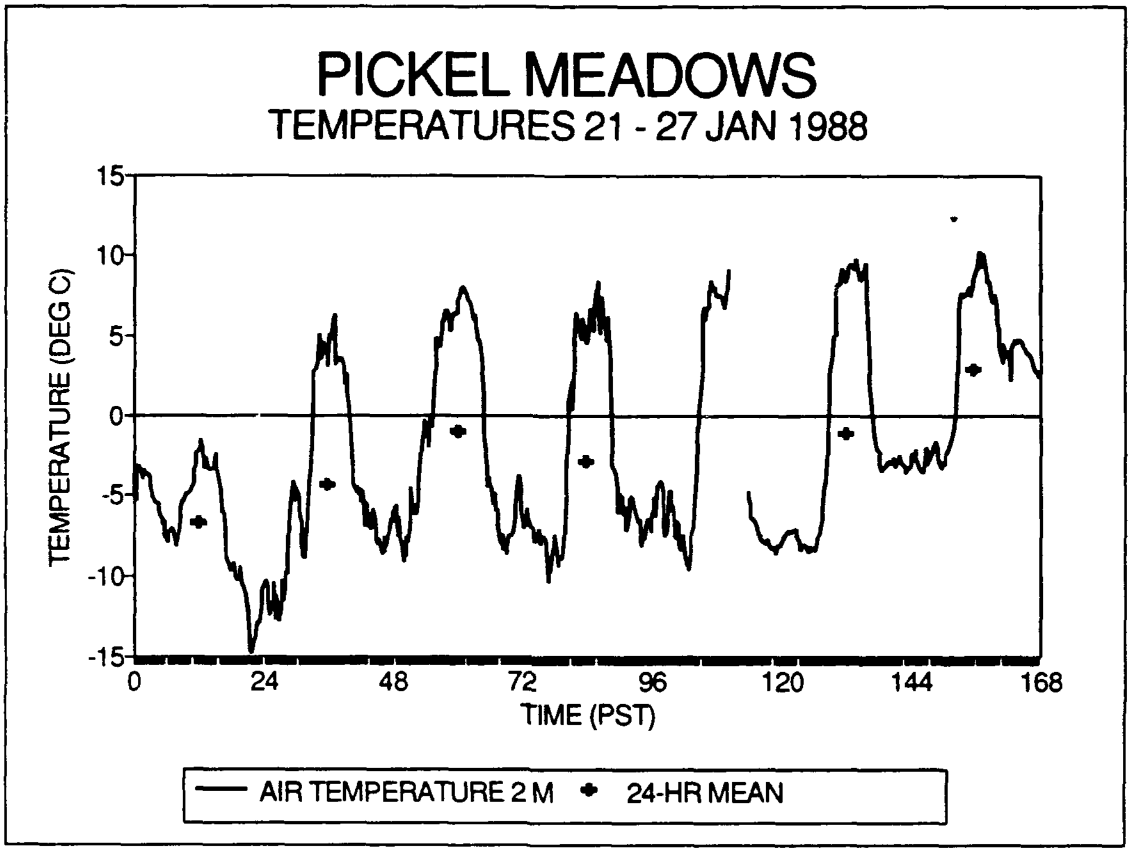


Figure 3 Six-day distribution of air and black globe temperature

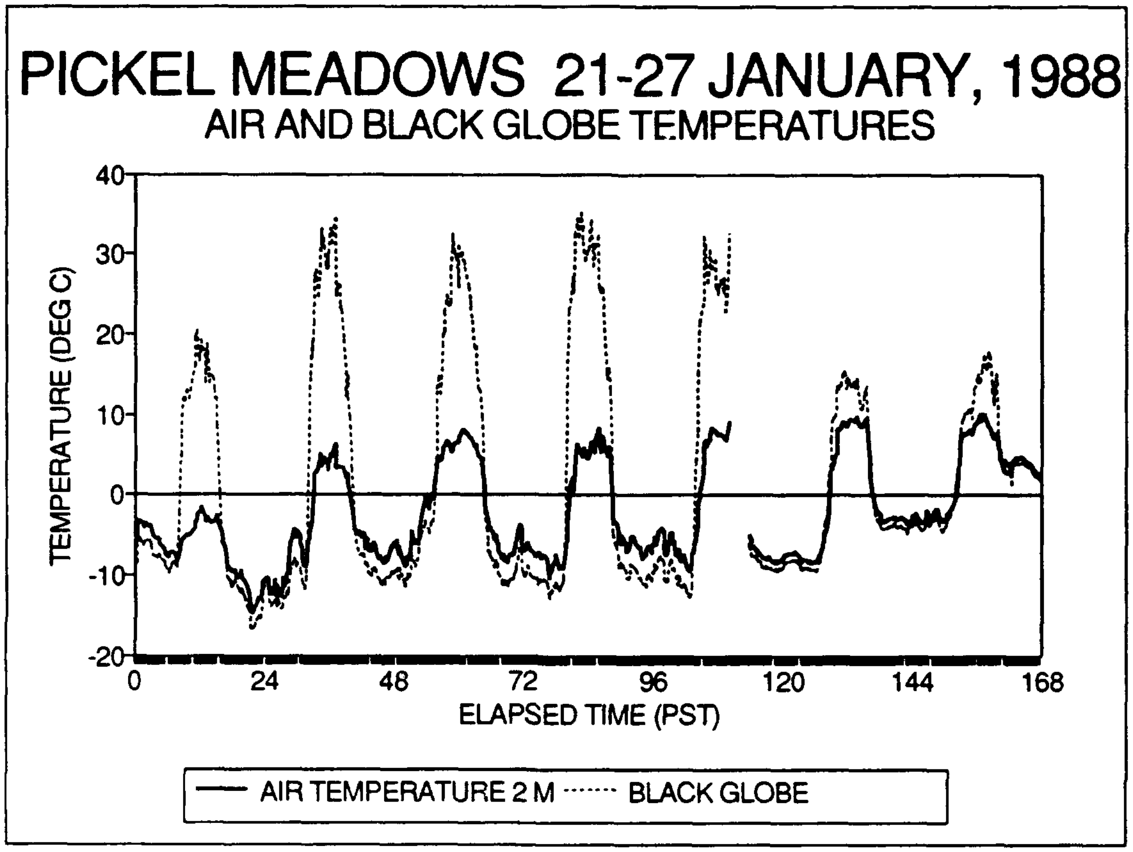


Figure 4 Six-day distribution of global solar radiation

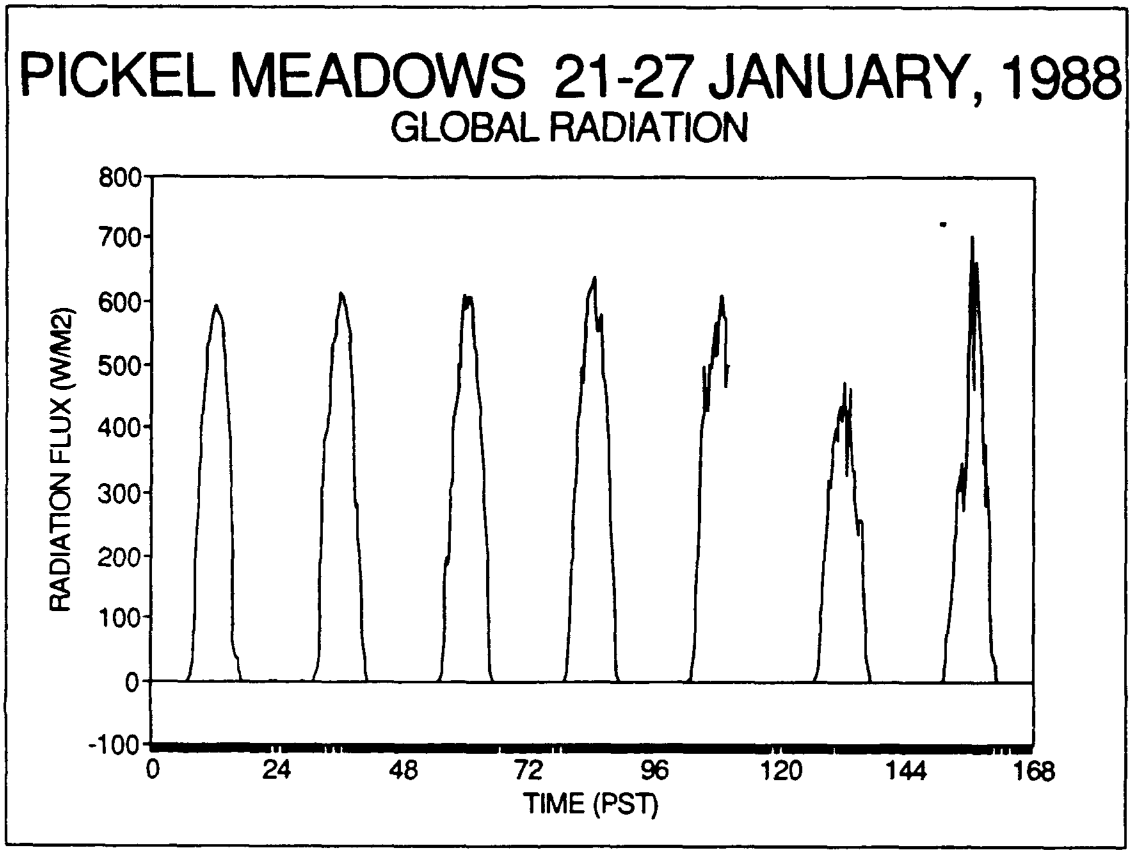


Figure 5 Six-day distribution of wind speed

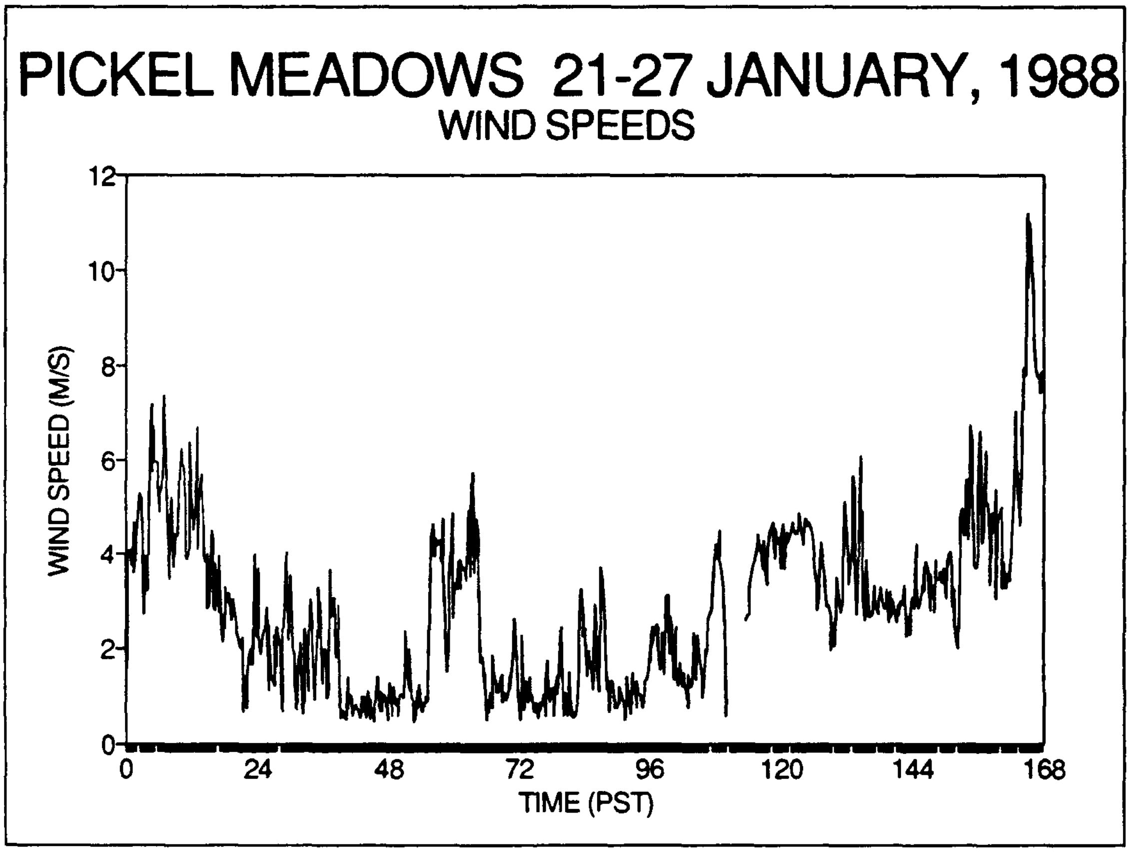
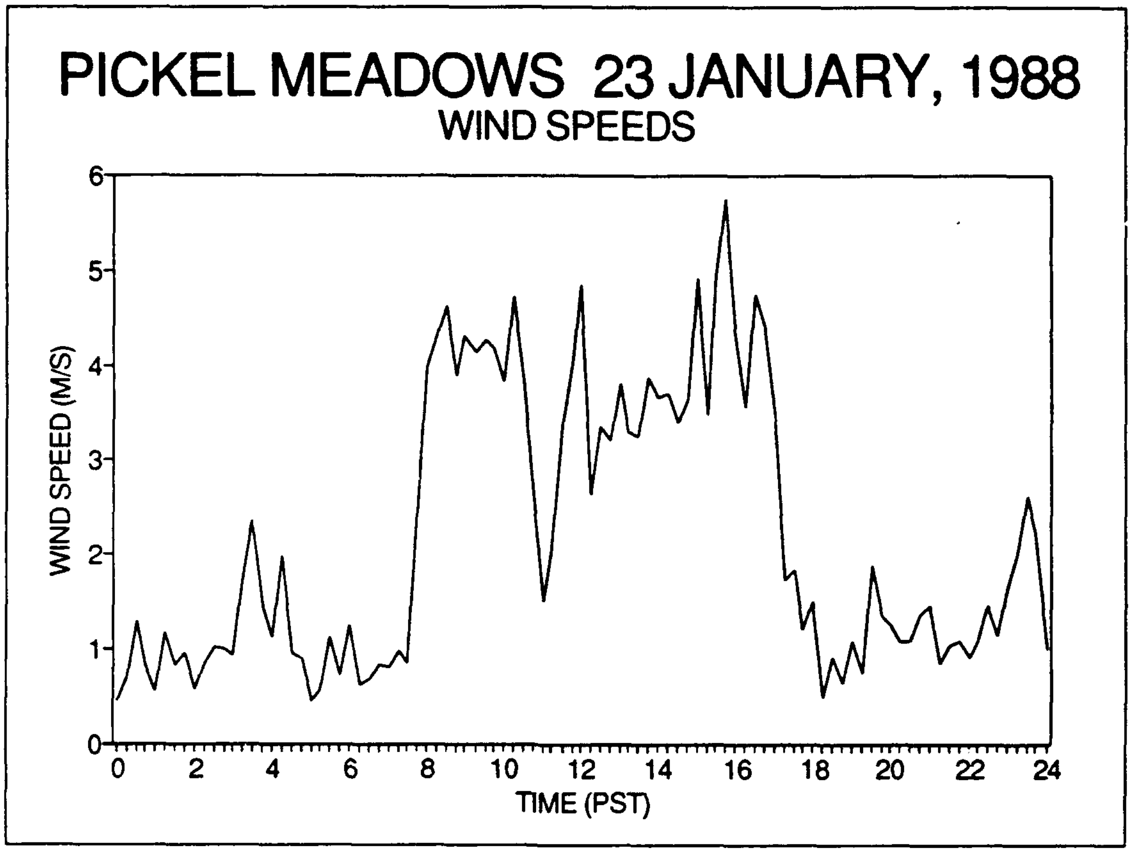


Figure 6 Wind-speed distribution on 23 January 1988



IV. DISCUSSION

A. Meteorological monitoring stations

In general, the requirements for meteorological monitoring in support of physiological studies are similar for both moderate and cold weather studies. The basic requirements are to monitor air temperature, wind speed, radiation and humidity. In cold weather, humidity is often neglected because sling psychrometers, which use distilled water, may not operate properly. Other humidity sensors, either electronic sensors such as electronic capacitance sensors, or hair hygrometers may be substituted.

The most basic weather instrument set may consist entirely of hand-held, non-powered instruments. By avoiding powered instruments, problems with maintaining batteries in cold weather are eliminated. However, the best meteorological data sets are collected using a complete weather station based upon an AC or battery-powered datalogger. An automated, electronic weather station permits data to be collected and averaged over shorter time intervals. The time interval depends on the length of the study and data requirements. The authors recommend a minimum 15 min interval for average values.

With an automated meteorological system it is relatively easy to collect more detailed data in terms of both sampling frequency. An automated station usually affords an opportunity to expand the number and sophistication of meteorological instruments. More temperature reading and back up or supplemental instruments can be added to the system. In regard to concerns of excessive data collection, the rhetorical response is to ask when there will be an opportunity to recollect the data? On-site meteorological data cannot be fully duplicated by other sources. Remote sensing data (usually weather satellites) are defined in terms of relatively large pixels and are often obscured by cloud cover. Also satellite data are dependent on the nature of the sensor platform. During operations, the platform may be stationary over the target area, but for routine field studies, the data may be dependent on the orbit of the sensor. Remote ground stations, such as weather stations located at local airports,

are often both too distant from study sites and fail to collect "human scaled" data. Record-keeping requirements also vary depending on the nature of the facility, so no presumptions should be made regarding the availability of meteorological data.

The degree of variability in meteorological data is dependent on the meteorological parameter and local terrain features. Level terrain with low, uniform vegetation, such as "desert pavement", plains or steppe, can be expected to be less variable than mountains, canyons or rolling, heavily vegetated hills. Coastlines along large bodies of water are strongly influenced by the proximity of the water.

Individual meteorological parameters vary in site sensitivity. In particular, local variations in wind speed and direction are very site specific. Humidity can be strongly influenced by local features, such as bodies of water or vegetation. Solar radiation is very predictable under clear sky conditions, and reasonable estimates can be made for overcast conditions. Variable partial cloud cover, especially associated with fast moving frontal activity, make solar radiation much more variable and less predictable.

B. Thermal models and indices

To individuals with a strong interest and commitment to the collection and use of meteorological data, the most intriguing claim is that it is unnecessary to collect and record meteorological data. One side of this argument is that relationships between meteorological conditions and human thermal state are "common sense", and that a combination of existing indices and common sense will suffice without specific data. It is indeed common sense that exposure to wind enhances heat loss and hence makes an individual colder. It is also common sense that it is warmer standing in the direct sunlight versus a shaded position. Common sense does not tell the user how wearing different amounts of clothing or activity will change human thermal balance and that dehydration and heat exhaustion are potential problems even in environments well below freezing.

The "wind chill index" (Siple and Passel, 1945) is the only widely accepted "model" that attempts to quantify the relationship between wind speed, air temperature and human physiological state. Wind chill is also probably the most abused empirical

index. It does not consider any impact of solar radiation or body posture and assumes a single constant air temperature as the forcing factor in cold stress. However, wind chill neither accounts for clothing nor activity, and relies on relatively primitive experiments involving freezing cans of water (Kessler, 1993). The basic problem with wind chill is that the basic predictions are misleading. Because there are so many extenuating variables, skin often does not freeze when predicted by wind chill (Kaufman and Bothe, 1986; Kessler, 1993). In short, wind chill expresses a worst case scenario that has little value beyond emphasizing the importance of wind speed (convection) in combination with air temperature.

Both scientific publications (Kaufman and Bothe, 1986; Kaufman, et al., 1987; Kessler, 1993) and the popular press (Irons, 1989) are critical of the wind-chill index. Uncritical application of the index may lead to errors. In FM-34-81 (1989) the critical value for troop safety is a wind-chill temperature of -25.6°F (-32°C). Whayne and DeBakey (1958) summarized U.S. Army cold injuries in WWII. They discuss wind chill, and essentially concluded that <u>because of insufficient data</u> it was not a useable concept in their evaluation. Kaufman and Bothe (1986) indicate that for "clothed" cylinders "our data for heat loss from the 'clothed' cylinder showed essentially no change with wind velocity, whether wet, protected by 'raincoat,' above or below freezing." This emphasizes the concern that the wind-chill index applies only to bare, exposed skin surfaces. USARIEM guidance (Young, et al., 1992) notes that wind-chill "only estimates the danger of cooling the ***exposed*** flesh of ***inactive*** persons" and that "windproof clothing greatly reduces windchill effects."

Whayne and DeBakey (1958) also discuss how changes in temperature and environmental moisture impacted the incidence of trenchfoot and frostbite. They note cases in which cold injuries shift from trenchfoot to frostbite injuries as environmental conditions change. When daily mean temperatures dropped below 50°F, trenchfoot was likely to occur. The authors made the interesting statement "the appearance of trenchfoot depends chiefly upon factors that enhance loss of body heat rather than upon low temperature per se." They also stated in regard to frostbite that it could be directly related to temperature, "It manifests itself almost immediately when the temperature falls below freezing." Wet-cold injury (trenchfoot, immersion foot) occurred well above those temperatures. Frostbite has also been related to troop movements through deep snow.

Whayne and DeBakey (1958) indicate only the two environmental thresholds for cold injury presented above. They note that trenchfoot injuries (a type of non-freezing cold injury) increases below 10°C and that 0°C is the upper limit for frostbite. USARIEM guidance (Young, et al., 1992) indicate that non-freezing cold injuries occur in wet-cold conditions between 32°F and 55°F (0-12.8°C) and freezing cold injuries occur below 32°F (0°C). In addition, they indicated limits for light-duty handwear at 0°C and provided guidance on the range for ECWCS (+40 to -60°F). They recommended that "black gloves", full head cover and VB footwear be worn below 0°F; noted that water containers will be frozen below -10°F, and recommended skis or snowshoes if snow depths are greater than 15 inches.

C. Other "models"

A better example of the scientific approach to the interaction of environment, clothing and human physiology is a plot in Gonzalez (1988) derived from Burton and Edholm (1955) showing the relationship of the clothing insulation required to maintain comfort at different levels of activity (metabolic heat productions) to air temperature. Another example of the scientific approach is a "Scholander" type plot (Scholander et al., 1950) that indicates the metabolic rate required to maintain homeostasis for resting organisms at varying air temperatures. By using meteorological data to construct "equivalent temperatures" which account for the effects of convective (wind speed) and radiative heat exchange, the Burton and Scholander plots can yield quantitative data regarding the impact of changing meteorological conditions on human thermal state and approximate clothing insulation requirements.

D. Current model development

The Burton and Scholander approaches date from the 1950s. Their results may be considered "models" in the sense that their methods attempt to quantify the relationship between the environment and human thermal state. Technically, the wind-chill index is also a model. The indices currently in use are simple models that incorporate predictive scales for applied operations. Relatively sophisticated models, such as operative temperature, existed prior to WWII. The problem with these more sophisticated models was that they required more than the simple pencil and paper mathematical skills that were available in the field. The wind-chill index was often available as a simple table. Today, with improved electronics, it is possible to make

relatively sophisticated estimates of thermal stress and predict the resultant thermal strain with a pocket-sized device. The problem is no longer a lack of mathematical expertise, but a problem of obtaining meteorological data.

Physiological models predict human responses to environmental stress, but also consider clothing and activity levels. Model derived thresholds are based on the resultant human condition, not directly on meteorology because we recognize that different combinations of meteorological parameters, plus the confounding effects of clothing and activity, will produce the same result.

A good environmental strain model synthesizes the impact of meteorology (environmental stress), activity level or task, clothing and physical condition of the soldiers to predict the resultant physiological condition. An applied model will also incorporate an operational interpretation of the results by predicting the negative impact of the combined conditions on soldier performance. Ideally, a program would also provide guidance regarding possible solutions, such as work-rest cycles, water requirements, initiation of rotation under cold exposure, better handwear, etc. Programs for estimating the impact of heat exposure, such as the P^2NBC^2 Heat Strain Decision Aid (HSDA), already exist. There is no published comparable whole body cold model.

In terms of new cold models, there are several new developments that hold promise. A series of limited models by USARIEM and TNO Institute for Perception (Soesterberg, Netherlands) predict hand or foot temperatures for specified conditions of clothing and activity level. USARIEM has a series of models which predict endurance time, i.e., time of exposure to reach a skin surface temperature limit of 5°C, which range in sophistication from a basic, Newtonian cooling model to cold induced vasodilation (CIVD) models which incorporate alternating pulses of warming and cooling (Shitzer, et al., 1990, 1991). TNO has a series of models which include a simple foot model and a hand-contact model. A NATO Research Study Group (RSG 20) is attempting to link a whole body cold model to a hand endurance model with clothing and limited meteorological data. Basic models to predict clothing insulation requirements also exist and Van Dilla, et al., (1949) presented a model for handwear endurance which is still utilized by some investigators.

V. SUMMARY

Historically, cold has been an important modifier of tactical operations. Therefore, for physiological studies of soldiers and their performance, it is important to incorporate meteorological data into field studies. The recommended standards for a meteorological database to support cold weather physiological studies should include four basic parameters; temperature, wind speed, radiation and humidity. There are two levels of meteorological data collection. The minimal standard would be a hand-held, non-electronic data collection instrument set. The minimum data-collection interval for a short-term study would be one hour. A more adequate standard would be an automated system based on an electronic datalogger and individual weather instruments. The recommended minimum sampling interval would be 15 min average data, although longer intervals may be desirable for some studies. An automated data collection system and the data collected in January 1988 during a winter field study are presented as a demonstration of meteorological data collection. The discussion also describes physiological models which utilize the meteorological data and presents shortcomings of the wind-chill index.

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APPENDIX A. Datalogger operating instructions and sample program

The following text continues the instructions to the weather station operator presented in the Methods section.

Programming the data logger: The basic data-logging program is attached. It should be recorded in the datalogger logbook along with identification of each instrument/input by channel and set-up height. To program use *1; to compile *0; to display the channels *6, then A (A to advance channels, B to reverse); *5 to set time; *4 to set printer (1:01) or tape output (1:10; both 1:11; disable 1:00); *8 to dump to tape; and *9 to dump to the printer. A 21X manual will be sent along to help operate the data logger.

Tape output: Data can be dumped continuously to a simple cassette tape or periodically, you can go around and dump all the storage into the cassette recorder. The cassette can be dumped directly into a data file through a "black box" at USARIEM; bypassing hand-processing of raw data. If the temperatures (0°C lower limit) are not affecting the recorder batteries, I recommend the continuous dump so that you have both a printer and tape record of data. To dump to tape, make sure that a dump is enabled (*4, 1:10 or 1:11), then check the storage (*7 will give you DSP). TPTR is initially 0 (or DSP+1 can be used). Plug in the recorder, push play and record buttons, attach to data logger and punch in *8 [*8:00,1:TPTR, 2:DSP, 3:(any key, then A)]. When finishing off a record (prior to moving the station or completing the study) do *8, 3A, 3A to dump the last few data points onto the tape. Check the manual for further details.

Program for winter meteorology station

	*1:10	10 second sample
1P	10	battery voltage check
	11	output or display channel
2P	17	reference temperature for thermocouples
	20	reference temperature location/output channel
3P	14	thermocouple temperatures (0,1,1.5,2 m plus T_{bb})
	5	5 repetitions or input channels
	1	sensitivity and voltage range

	2	position of initial input channel (2) in sequence
	1	thermocouple type (Type T copper-constantan)
	20	reference temperature location (channel 20)
	2	initial display or output channel (2)
	1	multiplier
	0	offset
4P	11	ground temperature sensor
	1	1 input
	1	input channel (1 High for single ended voltage)
	1	excitation channel (1)
	1	output or display channel (1)
	1	multiplier
	0	offset
5P	2	pyranometer (global radiation)
	1	1 input
	12	sensitivity and voltage range
	7	input channel
	7	output or display channel
	87.21	multiplier (Eppley #10132)
	0	offset
6P	2	pyranometer (Shadowband or diffuse radiation)
	1	1 input
	12	sensitivity and voltage range
	8	input channel
	8	output or display channel
	91.56	multiplier (Eppley #10129)
	0	offset
7P	1	barometer
	1	1 input
	15	sensitivity and voltage range
	2	input channel (2 single ended (1 Lo))
	9	output or display channel
	0.0207	multiplier (kP)
	0	offset
8P	3	anemometer (MET One)
	1	1 input
	1	pulse counter input channel
	2	configuration
	10	output or display channel
	0.1596	multiplier
	0.447	offset

9P	92	Set timer
	1	time into interval for record (1 min)
	15	averaging interval (15 min)
	10	internal flag
10P	77	enter time
	110	code for date (Julian), hour and minute
11P	71	print averages
	11	number of channels in sequence
	1	first channel in sequence
*0		to compile program
*6		to display LCD channels
	A	to start display in channel 1
		(A to advance, B to back-up)

Print-out	LCD display	input channel	instrument or data
1	---	---	internal timer or storage
2	---	---	Julian date
3	---	---	time: hour:minute
4	1	1 Hi	ground probe
5	2	2	T_a 0.5 m
6	3	3	T_a 1.0 m
7	4	4	T_a 1.5 m
8	5	5	T_a 2.0 m
9	6	6	T_{bg}
10	7	7	global radiation
11	8	8	shadowband
12	9	1 Lo	barometer
13	10	1 Hi pulse	anemometer
14	11	---	battery check

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